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Lunar and Planetary Laboratory

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PRINCIPAL INVESTIGATOR: Tom Gehrels   Feb. 15, 2001
Date

Tom Gehrels
Professor
Lunar and Planetary Laboratory
University of Arizona
Kuiper Space Sciences Building
1629 East University Boulevard
Tucson, AZ 85721-0092
Phone: 520/621-6970
FAX: 520/621-1940
Email: tgehrels@lpl.arizona.edu

BUSINESS REPRESENTATIVE: Ms. Lynn A. Lane
Senior Business Manager
Lunar and Planetary Laboratory
University of Arizona
Kuiper Space Sciences Building
1629 East University Boulevard
Tucson, AZ 85721-0092
Phone: 520/621-6966
FAX: 520/621-4933
Email: lynn@lpl.arizona.edu

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Participating Professionals (all at the Lunar and Planetary Laboratory):

Terrence H. Bressi (B. S., Astron. & Physics)	Engineer
Anne S. Descour (M. S., Computer Science)	Senior Systems Programmer
Tom Gehrels (Ph. D., Astronomy)	Professor, observer, and PI
Robert Jedicke (Ph. D., Physics)	Principal Research Specialist
Jeffrey A. Larsen (Ph. D., Astronomy)	Principal Research Specialist and observer
Robert S. McMillan (Ph. D., Astronomy)	Associate Research Scientist & observer
Joseph L. Montani (M. S., Astronomy)	Senior Research Specialist and observer
Marcus L. Perry (B. A., Astronomy)	(Chief) Staff Engineer
James V. Scotti (B. S., Astronomy)	Senior Research Specialist and observer

PROJECT SUMMARY

The purpose of this grant was to bring the Spacewatch 1.8-m telescope to operational status for research on asteroids and comets. This objective was achieved; first light with the telescope was in May 2000 and since then several tests and demonstrations of the facility's capability to observe Earth-approaching Asteroids (EAs) have been made, including the first observations to be incorporated into a peer-reviewed publication. The Spacewatch 1.8-m telescope will be the largest in the world dedicated full time to finding and doing astrometry of asteroids and comets. It will be used to search for asteroids and comets anywhere from the space near Earth to regions beyond the orbit of Neptune, and to do astrometry and lightcurves on the fainter of such objects that are already known. Its comparatively large aperture will permit faster discovery of the very small asteroids in Earthlike orbits, such as 1998 KY_{26}, that are coveted for their accessibility as material resources in space, as well as recovery of EAs on their return apparitions when they tend to be more distant and fainter than they were at the times of their discoveries. It will also tend to find EAs when they do not happen to be close to Earth. Discoveries made under those circumstances allow the objects to be followed for longer intervals, providing better determinations of their orbits during their discovery apparitions. In addition to its size, the 1.8-m Spacewatch telescope will have the unique capability of long strip scanning in any direction, for example along the ecliptic (the plane of the solar system), and along the line of variation of EAs with uncertain orbits that are being targeted for recovery.

PURPOSE AND JUSTIFICATION

The purpose of the Spacewatch project is to explore the various populations of small objects throughout the solar system. Statistics on all classes of small bodies are needed to infer their physical and dynamical evolution. More Earth Approachers need to be found for spacecraft missions and to assess the impact hazard. (We have adopted the term "Earth Approacher", EA, to include all those asteroids, nuclei of extinct short period comets, and short period comets that can approach close to Earth. The adjective "near" carries potential confusion, as we have found in communicating with the media, that the objects are always near Earth, following it like a cloud.) Persistent and voluminous accumulation of astrometry of incidentally observed main belt asteroids (MBAs) is permitting the Minor Planet Center (MPC) to determine the orbits of large numbers (tens of thousands) of asteroids. Such a large body of information will ultimately allow better resolution of orbit classes and the determinations of luminosity functions of the various classes. Comet and asteroid recoveries are essential services to planetary astronomy. Statistics of objects in the outer solar system (Centaurs, scattered-disk objects, and Trans-Neptunian Objects; TNOs) ultimately will tell part of the story of solar system evolution. Spacewatch led the development of sky surveying by electronic means and has acted as a responsible interface to the media and general public on this discipline and on the issue of the hazard from impacts by asteroids and comets.

BACKGROUND

CCD scanning was developed by Spacewatch in the early 1980s, with improvements still being made. Spacewatch was the first astronomical group to use drift scanning with a CCD, first to use CCDs to survey the sky for comets and asteroids, first to do astrometry on an asteroid with a CCD (1984 JZ on 1984 Apr. 28; numbered (3325) after our observation), first to do targeted astrometry of an EA with a CCD (1983 TB, now known as (3200) Phaethon, on 1984 Sep. 22), first to discover an asteroid with a CCD (the Trojan (3801) Thrasymedes), first to discover an EA with a CCD (1989 UP), first to discover an EA with software (1990 SS; now (11885)), first to discover a comet with a CCD (1991x; modern designation 125P/1991 R2), and first to discover an asteroid known to be monolithic (1998 KY_{26}). At the time of this writing, Spacewatch still holds the records for discovering the smallest known asteroid (1993 KA_2; H=29), the closest known approach of any asteroid to the Earth (1994 XM_1; 105,000 km), the object with the most Earthlike orbit (1991 VG), the largest TNO other than Pluto (2000 WR_{106} = minor planet (20000)), and the asteroid most accessible to spacecraft (the rapid rotator 1998 KY_{26}). As of 2001 Feb. 9, Spacewatch had discovered 232 EAs, 16 Centaurs or scattered-disk objects, 17 comets, 7 TNOs, and rediscovered one lost comet (P/Spitaler in 1993). Since 1984, Spacewatch has also made a total of 4,255 astrometric observations of comets, recovered 61 comets, and has reported 320,214 astrometric detections of asteroids, mostly in the main belt, including more than 42,161 for which provisional designations have been credited by the MPC to Spacewatch. A total of 5,051 positions of EAs have been reported by Spacewatch since 1989.

TECHNIQUE

Moving objects are discovered by scanning the sky with a charge-coupled device (CCD) electronic imaging detector on the 0.9-meter Spacewatch Telescope of the Steward Observatory, University of Arizona, located on Kitt Peak mountain in the Tohono O'odham Nation. Now that the 1.8-m telescope is complete, similar observations will be made with it also. The principles of Spacewatch observing have been described by McMillan and Stoll (1982), Frecker *et al.* (1984), Gehrels *et al.* (1986), McMillan *et al.* (1986), Gehrels (1991), Rabinowitz (1991), Perry and

Frecker (1991), Scotti (1994), and Jedicke (1996). Each Spacewatch scan consists of three passes over an area of sky using a CCD filtered to a bandpass of 0.5-1.0 μm (approximately V+R+I with an effective wavelength on typical asteroids of 0.7 μm). The effective exposure time for each pass is 143 seconds multiplied by the secant of the declination. The area covered by each scan is 32 arcminutes in declination by about 28 time minutes in right ascension. The image scale is 1.05 arcseconds per pixel. Three passes take about 1.5 hours to complete and show motions of individual objects over a one hour time baseline. The limiting magnitude with the 0.9-m telescope on slowly moving objects in good conditions is about 21.8. More than 2000 deg^2 are now being surveyed per year with the 0.9-m telescope, and this practice or a similar procedure will be adopted with the 1.8-m telescope.

ACCOMPLISHMENTS

1.8-meter Telescope: The telescope is described by Perry *et al.* (1996), McMillan (1998), McMillan *et al.* (1998), Perry *et al.* (1998), McMillan *et al.* (2000), and the Spacewatch web site *http://www.lpl.arizona.edu/spacewatch*). The mechanical design of the telescope is optimized by finite-element analysis to provide high resonant frequencies. The mount is an altitude-azimuth type for compatibility with the mirror support cell contributed by the Multi-Mirror Telescope Observatory. The telescope and mount were fabricated in the University Research Instrumentation Center of the University of Arizona. Both axes are driven by DC servo motors directly coupled to friction rollers. The azimuth and elevation motors as well as the CCD instrument stage are under computer control with low-level software provided by the Galil Motion Control Co. and high-level software written by our Engineer Terry Bressi.

Optics: The optical configuration is f/2.7 folded prime focus with a flat secondary that locates the focal plane in the center of the optical trusswork near the altitude axis. This shortened the telescope enough to make the dome building affordable, and the flat secondary preserves the fast f/number of the primary mirror. The coma corrector designed by R. A. Buchroeder is a modified Klee design of 5 spherical lens elements plus a Schott OG-515 filter transmitting longward of the B bandpass. The filter greatly simplified lens design and reduces sky background while not significantly reducing the brightness of asteroids. The distortion-free, flat, unvignetted field of view is 0.8 deg in diameter and the image scale is 1.0 arcsec/24 micron pixel.

Detector: An SI424-AB1-1 thinned, back-illuminated, antireflection-coated 2Kx2K CCD of excellent cosmetic quality was obtained from Scientific Imaging Technologies, Inc. of Beaverton, OR. This detector fills the available field of view of the 1.8-m telescope, and according to the vendor's quality control sheet it is cosmetically almost perfect, being devoid of column or row defects. The cryostat and electronic controller and readout system are being tested in our lab. Cooling is by closed-cycle gas circulation, eliminating handling of liquid nitrogen. This system will be able to drift scan up to twice the sidereal rate, as well as scan at subsidereal rates for more sensitivity. A 5-second readout from four quadrants simultaneously also permits efficient operation in "stop-and-stare" mode.

Image Analysis Software: The software to be used at the 1.8-m telescope will be a modified version of that which has been in use at the 0.9-m telescope. Larsen and Descour developed IMPACT: Image Motion Package for Asteroids, Comets, and Transneptunians (Larsen *et al.* 2001 in preparation). IMPACT has an advantage over the peak-pixel detection algorithm in the 1990-vintage MODP software in that it requires that several pixels above threshold be spatially correlated in order to qualify as a detected image. As a result, IMPACT can find fainter objects. Since 1999 Sept. 29 it has been in use at the 0.9-m telescope. It finds 40% more asteroids per scan, brings the efficiency for V<20 to above 90%, affords 0.2 mag more sensitivity, and can detect smaller angular displacements than MODP. At the 1.8-m telescope, it will be used in a greater variety of modes, including scanning at subsidereal and supersidereal rates and long "staring" (sidereally tracked) exposures. Staring mode observations have already been made with this software at the 0.9-m telescope.

Limiting V mag with the 1.8-m telescope will be 22.5 while scanning at the sidereal rate. In that mode the rate of coverage of sky will be 2000 deg^2 per year. Fainter magnitudes can be reached in longer "staring" exposures, while area coverage can be double that with fast scanning.

First Light Observations:

2000 May 3 - 1.8-meter First Light was focused starlight on a ground glass slide.

2000 June 15 - Stars were acquired with a video camera. The pole star (Polaris) was found and positively identified. About six other stars were acquired, moving progressively further away from the pole until the objects couldn't be found.

2000 September 14 - First asteroid light on 1.8-meter: A Panasonic low-light video camera was used to capture images of the very fast moving object (VFMO), 2000 RD_{53}. Integration time was approximately 0.5 seconds per frame, thus there were very few stars in the field.

2000 September 15 - First digital data with 1.8-meter: The rotation stage is working, plus focus, tip & tilt. We videotaped the focusing on a cluster, and then replaced the video camera with an SBIG ST-6 cooled digital CCD camera. We got some star fields and saved the images.

2000 September 19 - First digital data on an asteroid with 1.8-meter: With the cooled digital ST-6 CCD camera at prime focus, we determined the zero point of the instrument rotator parallactic angle and acquired every object we pointed at without searching. We observed some Landolt photometric standards as well. The high point of the night was our acquisition of the very fast moving NEO 2000 RD_{53}. We recorded several images showing its trail, thereby simultaneously achieving for the 1.8-meter telescope the first digital data on an asteroid, the first observation of an NEO, the first observation of a "Very fast moving object" (VFMO), and the first observation of a potentially hazardous asteroid (PHA).

2000 September 20 - First data with potentially scientific value: We made a two hour series of photometric measurements of the VFMO 2000 RD_{53}.

2000 September 28 - Another lightcurve: We made the most interesting observations with the 1.8-m telescope yet. The drive software is now capable of tracking on a fast moving asteroid (2000 SM_{10}), and we got more than 3 hours of measurements of its apparent magnitude. These data will be incorporated into a peer-reviewed publication (Pravec *et al.* 2001, in preparation).

2000 Nov. 22 - Collimation: We got some images on the small ST-6 CCD (4 x 6 arcmin) thru beautifully clear sky and excellent seeing (as reported by Montani on the 0.9-m telescope). The purpose of these observations was to examine the image quality at the uncorrected prime focus after the LPL Shop's collimation of the primary and secondary mirrors to plumbed laser beams, and before the coma corrector was installed.

The images across the ST-6 field are uniform, round, and focusable down to 2 arcsec FWHM or better. There is no evidence of coma in the realtime displays, which indicates the optical axis is very close to the center of the CCD, unlike the September images. We also took a 5 min exposure with the rotation stage not rotating, to see where the arcs traced out by the stars are centered. The image rotation axis seems to be not far beyond one corner of the CCD.

2000 Dec. 14 - Prime focus collimated: Mostly clear, and Tubbiolo reported 3 arcsec seeing at the 0.9-m. We acquired focus near the middle of the range and the images look great - at least as good as before Thanksgiving. So the secondary mirror is now where it needs to be, and the primary and secondary are well collimated.

2001 Jan. 24 - We did the first successful test of the whole optical system of the 1.8-m telescope, including the 6-element coma corrector lens system. Previous observations with this telescope were made at prime focus, without the lenses that are needed to correct for the coma that is a property of any parabolic primary mirror. The coma corrector is designed to give good images over the full 0.8 degree wide field of view. To evaluate the images over this wide a field using the small SBIG ST-6 CCD, we located the detector at 5 positions: on axis, and 4 positions corresponding to the corners of our bigger science detector that we plan to install soon. The images we took of the open cluster χ Persei are seeing-limited both on and off axis, showing that the optical design as well as the lens fabrication and the collimation of the whole system have been successful.

Construction of the Spacewatch Telescope was funded by grants from the Department of Defense Clementine Program, NASA, the University of Arizona Foundation, and other private and corporate donors. The dome and building was funded by the David and Lucile Packard Foundation, the University of Arizona Foundation, and John and Ilene Nitardy of Seattle, WA, and was dedicated as the David and Lucile Packard Building.

Building and Dome:

The building was not funded by NASA, but NASA provided funds for salaries of Spacewatch personnel who guided the design and supervised the construction. The building is completely outfitted with pier, dome, electrical wiring, plumbing, telephone, fiber optic ethernet hookups, and lightning protection. The building structural frame is made of steel and the walls are Galvalum®, an aluminum-coated sheet steel product. The dome is also made of Galvalum®. In addition to being maintenance-free, Galvalum® also has a high reflectivity, a low thermal inertia, and a low thermal emissivity. This means it will not heat up much in the daytime and will not chill down below the temperature of the ambient air at night. These are important properties for an observatory. The building is elevated well above grade to minimize the cost of site preparation, to minimize the effects of convective cooling of the ground on observing, and to prevent the heat buildup that might occur in an enclosed ground floor, the cooling of which would disturb the nighttime seeing.

The southwest wall of the building is flared out to admit air flow. Two powerful fans in the opposite (northeast) wall are used to draw outside air into the building through the openings, and/or through the open dome slit during observing. This is to prevent heat buildup in the building with its attendant convective cooling that would interfere with the imaging by the telescope.

The building has about 1105 square feet of usable floor space on a main floor plus a mezzanine deck. A control room in the north corner is about 282 square feet in size and is ventilated by a ducted blower to prevent heat from the computers and monitors from elevating the temperature.

Windows are provided to aid illumination of engineering work in the daytime. The windows cannot be opened and are equipped with blackout shades so when the lights need to be turned on at night to work on equipment, they do not interfere with the work of the other telescopes on Kitt Peak.

The dome has a full 360° set of electrified rails so the dome shutter can be opened or closed at any azimuth position of the dome, and to provide lights on the inside surface of the dome. The shutter opening is 90 inches across to permit easy centering of the 72-inch diameter telescope aperture and to admit plenty of outside air to equilibrate the temperature around the telescope.

For protection against lightning, the building is equipped with static electricity dissipation rods grounded through heavy gauge copper braid wire to copper plates buried under the concrete footings of the building uprights. A Transtector® electrical surge absorber prevents the transmission into the building wiring of all but a direct hit by lightning. Fire protection is provided by smoke detectors which cut all the electrical power to the building when smoke or fire is detected, at which time battery-powered emergency lights come on. This system also has an alarm audible outdoors and an automatic telephone dialer.

EDUCATION, PUBLIC OUTREACH, AND MEDIA CONTACT

These contributions by Spacewatchers are made without any compensation over and above their regular University salaries.

Gehrels teaches "Universe and Humanity, Origin and Future," every spring semester for undergraduate students at the University of Arizona and is developing a textbook for that. He also continues with other duties such as the Dean's P&T Committee, the Graduate Certification Committee and as a Marshall at all Commencements. Decades of service on the Van Biesbroeck Committee came to an end in July 1997 when the Award was handed over to the American Astronomical Society. At the University of Arizona Press, Gehrels was the founder and General Editor of the Space Science Series, which resulted in 30 volumes, until Rick Binzel took over in the Fall of 2000 with the preparation of "Asteroids III" and "Comets II." Gehrels was the Principal Investigator of Spacewatch until he handed that over to McMillan on June 7, 1997, after which he has been continuing as an observer.

In India, Gehrels continues as a Sarabhai Professor for consulting and lecturing such as in a UN Course for graduate students from Bolivia, India, Indonesia, Kazakhstan, Kyrgizstan, Mongolia, Nepal, North Korea, Sri Lanka, and Uzbekistan. His base is at the Physical Research Laboratory in Ahmedabad; there are side trips to other institutions such as the Indian Institute of Astrophysics in Bangalore. The interaction with the students and colleagues continues by e-mail throughout the year. The paper of Bhandari and Gehrels (1999) resulted from this.

On the way to and from India there always are stops and engagements such as in 1997 for 6 lectures on comets and asteroids in 6 different places in Japan at the request of Dr. Isobe in preparation for his NEO observatory. In July 1998 there was the meeting of the American Geophysical Union in Taiwan, from which the statistics paper resulted (Gehrels 1999).

In this grant period, the publication of results from Pioneers 10 and 11 came to an end, and also the Palomar-Leiden Surveys of asteroids and Trojans. The Spacewatch program is the CCD-based successor of the latter.

There were numerous interviews, some 15 television shows in this period alone, primarily on the hazard aspect of the asteroids. Gehrels' theme of public lectures usually is "Origin and Evolution of Comets and Asteroids."

Kitt Peak is in the Tohono O'odham Nation, where construction of buildings is normally subject to the Tohono O'odham Employment Rights Ordinance (TERO) that ensures employment of tribal members on construction projects. Although the UA, as part of the State of Arizona, is probably exempt from that ordinance, the Spacewatch Project voluntarily complied with it to ensure that members of the tribe would participate in this expansion of the Project. The resulting collaboration between the UA and the Tohono O'odham Nation includes continuing presentations by Gehrels to hundreds of students of the three high schools of the Nation. A specific goal is to eventually have a Tohono astronomer at the 1.8-meter; Gehrels has a 20-year wager running on that with the Director of TERO. The way to reach this goal and win the wager is to get the students enrolled in the Summer Camps directed by Astronomer Don McCarthy of the Steward Observatory. (So far no luck, but we have 16 years left to succeed.)

Larsen invested considerable time training, coaching, employing, and tutoring students, especially the seven who are working or did work for Spacewatch: Natasha Carpenter, Nichole Danzl, Anne Descour, Arianna Gleason, Mike Read, Andrew Tubbiolo, and Ben Zuniga. Danzl and Gleason have discovered EAs, Centaurs, and TNOs, while Descour did a magnificent job of programming the IMPACT software interface. After obtaining her MS in Computer Science, she was hired by us as a full time Senior Systems Programmer. Read and Tubbiolo's work with computer hardware and electronics made it possible to modernize the data system at the telescope, and they are both now also trained solo observers.

Larsen hosted numerous visits by colleagues and fans of Spacewatch to the telescope, most notably to two groups from Raytheon Corp. and two groups of UA biologists. He gave a number of interviews for radio, TV, and news magazines. These included *The Arizona Daily Star's* science writer Jim Erickson and *Sky & Telescope's* Associate Editor Stuart Goldman on the topic of the discovery of the 17th moon of Jupiter, Jens Ramskov, Ph. D., of *Ingeniøren* (Engineering Weekly) of Denmark, Karelle Plummer, Jr. Exec. Producer of "Now Channel" in the UK, and Sofia Loverdou of "Greek Newspaper" on the topic of Spacewatch's rediscovery of the lost asteroid (719) Albert. Larsen was also interviewed by the University of Minnesota University Relations about naming minor planet (10172) after Prof. Roberta Humphreys. That was carried at least on the Tucson ABC-TV affiliate and published in *The Tucson Citizen, The Minneapolis Star*, and *The Minneapolis Tribune.* In addition, Larsen gave an email interview about NEAs to a freelancer, contributed to a press release by LPL's Agnieszka Przychodzen about Spacewatch research on Centaurs and TNOs, and gave an interview to Jorge Ianiszewski from *Circulo Astronomico* about Spacewatch's TNOs.

Larsen answered hundreds of questions from the general public received through access to our web site and contributed a piece to Benny Peiser's "CCNet" listserve on the asteroid impact hazard. Larsen's development of the Spacewatch web site (*http://www.lpl.arizona.edu/spacewatch*) was rewarded by awards from Key Resource, StudyWeb, and Scout Report Selection services.

Larsen also gave two talks at the U. S. Naval Academy in Annapolis, Va. and a colloquium at the Univ. of Minnesota. He is coaching a faculty member and midshipmen at the Naval Academy to observe asteroids with their small but modern telescope. As a successful graduate of University of Minnesota - Morris, Larsen was asked to reminisce about what their campus was like in the "dark ages" of 1985-1989. (His response included the fact that he had to walk 10 miles uphill to school each way in the snow.)

McMillan, Perry, Bressi, Scotti, and students Mastaler, Read and Tubbiolo, and Administrative

Assistant T. M. Lane of Spacewatch spent considerable time communicating with and training an astronomer from the Ulaan Baatar Observatory in Mongolia. This effort is funded by a grant from AFOSR. The purpose of this education is to develop the capability for astronomers in Mongolia to observe asteroids. This has been given a high priority by DoD/Pentagon.

McMillan gave video interviews for Phoenix commercial TV, UA News Services, the Tucson affiliates of NBC-TV and PBS-TV, and the RSK program of Sanyo Broadcasting Co. of Japan. He did an interview with reporter/still photographer Kazuya Nagase of Kyodo News of Japan. He contributed to press releases and interacted extensively with the press on the topics of Spacewatch's rediscovery of the long-lost asteroid (719) Albert and the Spacewatch discoveries of S/1999 J1 (a satellite of Jupiter) and 2000 WR_{106}, the brightest known TNO other than Pluto. McMillan and Montani hosted and assisted a still photography crew for *Worth Magazine* at the Spacewatch telescopes. McMillan also gave tours of the Spacewatch telescopes for participants of a Mars Conference, a meeting of chemists, an assemblage of UA Dept. Heads, an advisory board to the UA College of Science, the Japan Spaceguard Association, and (with Gehrels and Read) a United Kingdom Task Force on Near-Earth Objects. This latter helped that Task Force write a thorough report to Her Majesty's Government on the hazard of impacts by asteroids that was also well received internationally. McMillan's presentations at the Space Studies Institute in Princeton, NJ and the Colorado School of Mines in Golden, CO reached students and members of the general public in addition to professionals. With Mike Read he upgraded the Spacewatch web page, and granted permission for many organizations, including planetaria, to use images from the page for media productions. McMillan gave talks on Spacewatch to Prof. Steve Tegler's physics class at Northern Arizona University in Flagstaff, to the Saddlebrooke retirement community near Tucson, and a class of senior students at Tucson High Magnet School. McMillan also provided technical advice to two science fiction writers.

Scotti gave several public lectures in this time period, including the Annual Dinner Meeting of the Ottawa Centre of the Royal Astronomical Society of Canada in 1998 November, a guest presentation and question and answer session at Vail Middle School in 1999 May, two phone lecture and question and answer sessions with Edison High School (Fresno, CA), and a public lecture in 2000 April at the Pima Air and Space Museum. Scotti's interaction with the press extended from phone interviews and conversations, to film interviews, to live radio call-in shows, magazine articles, and numerous web/e-mail related interactions, including several for stories in newspapers or web publications. These were mostly for the (719) Albert story, but there were also some on the impact hazard. He was interviewed on national TV in 1998 on the 1997 XF_{11} affair, and wrote an article on his discovery of that closely-approaching asteroid for *Sky and Telescope* magazine (Scotti 1998). Scotti did a radio interview on "Let's Talk Stars" on KTKT with David Levy on Sept. 12, 2000, a radio interview on KXAM (Phoenix) with Dr. Sky (Steve Cates) on Nov. 24, 2000, and a video interview for "Savage Planet". He was interviewed by Jim Erickson of *The Arizona Daily Star* for the (719) Albert story.

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SPACEWATCH PUBLICATIONS, 1996-2001

Spacewatch reported 194,556 astrometric detections (1 "detection" usually equals 3 "positions") of asteroids and comets to the IAU's Minor Planet Center (MPC) in Cambridge, MA from 1996 December 1 through 2001 Feb. 3 inclusive. Half of these the MPC has already published in the *Minor Planet Circulars,* with a resulting 26,506 object designations. A total of 1,942 positional measurements (611 detections) were made of Earth-Approachers (EAs), 101 of which were new Spacewatch discoveries reported in the *Minor Planet Electronic Circulars* (MPECs). Spacewatch also discovered 12 Centaurs/Scattered-Disk Objects, 7 TNOs, 13 comets, and an outer satellite of Jupiter (the smallest known) during this report period. Those discoveries were all published as MPECs. We do not list all the MPECs here.

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